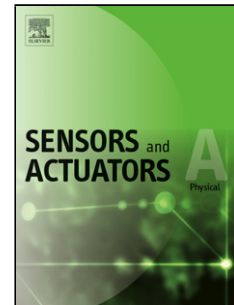


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# Design and test of Geophonino-3D: A low-cost three-component seismic noise recorder for the application of the H/V method

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## **Highlights**

- Low cost data acquisition system for recording three-component seismic noise.
- Suitability of the equipment for the application of the H/V method.
- The developed system has been successfully compared with commercial systems.
- It is an open source and open hardware system.
- The low cost is essential for small research groups with reduced economic support.

## **Abstract**

Earthquake effects are strongly related with the properties of the local geology, amplifying the ground motion, especially in soft soils. This amplification is connected with the resonant frequency, which can be estimated applying the horizontal-to-vertical spectral ratio (H/V) method on seismic noise measurements. In this work, a low-cost user-friendly data acquisition system (Geophonino-3D) has been designed for three-component seismic noise recording. The developed system consists of the signal conditioning circuit and the Arduino Due with an SD Shield for data storage. The suitability of the equipment for the application of the H/V method has been first assessed in the laboratory, according to the experimental sensitivity, the internal noise stability and the channel consistency. Subsequently, experimental verification has been carried out by recording seismic noise at eight different sites along the province of Alicante (southeast Spain), with different soil characteristics. The performance of the developed acquisition system has been evaluated in terms of the power spectral density and the H/V peaks by comparison with the results obtained through a commercial seismic recorder. The obtained results show the applicability of the developed acquisition system to record seismic noise and to apply the H/V method. Geophonino-3D is an open source and open hardware system and the price of its components is much lower than any other commercial equipment, which becomes a significant advance especially for small research groups with reduced economic support.

**Keywords:** Seismic data acquisition; H/V method; seismic noise; Arduino Due; open-source system

## 1. Introduction

Recent studies all over the world have shown the importance of the local geology in the earthquake disasters and their consequences. Depending on the particular characteristics of the subsoil, the ground motion might be drastically amplified, increasing the earthquake effects. Therefore, soil characterization becomes a crucial issue on seismic hazard studies, particularly in urban areas located on soft sediments (e.g. [1-3]).

Subsoil characterization can be carried out through different methods, basically classified in geotechnical and geophysical techniques. Among the second group, passive seismic methods based on seismic noise measurements have become very popular in the last decades, since they constitute a non-invasive and low-cost tool especially suited for urban areas [4].

The H/V method, also called Nakamura technique [5], requires only the acquisition of seismic (or ambient) noise by a three-component station. The two horizontal components are combined and then, the horizontal-to-vertical spectral ratio is calculated. The required seismic noise measurements can be taken nearly everywhere, even in urban areas, and for relatively short periods of time [6]. The H/V method provides insights of the site response due to the good correlation that exists between the H/V frequency peak and the fundamental resonance frequency of the soil column at the site, in 1D media [7]. The usefulness of this technique has been highly demonstrated in numerous works, with particular application to urban areas [8-9].

Although the application of this technique only requires a three-component sensor with the corresponding data acquisition system, the cost of both devices implies a substantial financial investment. Therefore, the development of reliable and low-cost instrumentation would make data acquisition more feasible for everybody, which could

be specially interesting for universities and small research groups with reduced economic support.

Recent advances in microcontrollers technology have helped some research groups to develop and produce their own purpose low-cost systems. For instance, Picozzi et al. [10] developed a dedicated seismic recorder for seismic arrays, which consisted of three main hardware parts: the sensors, the digitizer board and a Wireless Router Applications Platform. All components were directly bought, excepting the digitizer printed circuit board, which was developed within the GFZ-German Research Centre for Geosciences. The whole system was cheaper than other commercial seismometers but even though the cost was still high (about 700€ per unit). More recently, a lot of applications in different research fields have been appearing in the literature based on popular devices such as Arduino (e.g. [11-14]), Raspberry Pi (e.g. [15]) or BeagleBone Black (e.g. [16]). In the field of seismology, Saraò et al. [17] have developed a low-cost Arduino based seismometer for educational purposes, although the sampling rate of the recorded signals is not constant and the units of the amplitude are not calibrated. In a recent research project of the authors [18], a 1-channel seismic recorder prototype based on Arduino has been developed and its suitability for active seismic has been assessed comparing its performance respecting to other commercial acquisition equipment: the DT321 PCI data acquisition board and the RAS-24 exploration seismograph. However, the 12-bits resolution of the A/D converter and the fixed voltage gain might become serious inconveniences when it is used for passive seismic applications, such as the H/V method.

In this work, we have chosen the Arduino platform because of its low price, the numerous shields available and the extensive online support network. The developed design incorporates a voltage-controlled amplifier, which allows adjusting the

amplitude of the recorded seismic noise to the appropriate dynamic range of the A/D converter. Besides, a double buffer has been configured by software to prevent from occasional jumps in the recorded samples. In any case, the capability and limitations of the Arduino based data acquisition system have to be explored in order to be more widely accepted and used.

The objective of this work is to determine whether the designed Arduino based data acquisition system, Geophonino-3D, formed by low-cost, off the shelf components, is suitable for recording the seismic noise needed for the application of the H/V method. The paper describes the development process as well as the standard functional tests established for commercial seismic recorders. Thus, several laboratory experiments are exposed in order to quantify sensitivity, internal noise stability and channel consistency. After that, experimental verification has been carried out by recording simultaneously with Geophonio-3D and a commercial recorder system, Reftek, at eight different sites along the province of Alicante (southeast Spain). The performance of both equipment has been compared in terms of the power spectral density and the H/V peaks. The obtained results demonstrate the suitability of the developed system for the acquisition of three-component seismic noise, in order to apply the H/V method.

## **2. Materials and Methods**

### *2.1. Hardware design*

The general scheme of the system developed for three-component seismic noise acquisition is shown in Figure 1. It basically consists of three main blocks: 1) A triaxial sensor; 2) amplifiers and filters for signal conditioning; and 3) Arduino Due with SD (Secure Digital) Shield for data storage and acoustic buzzer.

The central device is the Arduino Due board microcontroller. It is a multipurpose open-source hardware platform, based on the Atmel SAM3X8E ARM

Cortex-M3 CPU. Some of their technical features include: 12 analog input pins, what allows connecting several input sensor signals; a CPU clock of 84 MHz, which allows a theoretical maximum sampling frequency of 1 MHz [19]; 512 Kb Flash memory and 96 Kb SRAM memory; and 54 digital I/O pins. In our case, four of these digital I/O pins are set up as outputs and they are used to control the cut-off frequency of the antialiasing filter (through a binary clock signal) and the voltage gain of the programmable gain amplifier (through a three-bit binary code), respectively.

The developed acquisition system, Geophonino-3D, is configured with three identical input channels, in order to record the three components of the ground motion. Between the sensor and the analog-to-digital converter of the Arduino Due board, a signal-conditioning block is required. Thus, each component of the signal (i.e. each channel) has to go through this block before being recorded. In Figure 2, the electronic scheme of the signal conditioning circuit is shown. This block is basically formed by three stages: 1) An instrumentation amplifier, INA155 chip; 2) an antialiasing filter, MAX7404, which is a 8th-order, low pass, elliptic, switched-capacitor filter; and 3) a programmable gain amplifier, LTB5 (6910-1). These three components can be power supplied through the 3.3V pin of the Arduino Due, which makes Geophonino-3D suitable for portable applications. The average current draw of the complete system during data acquisition is 290mA.

The INA155 chip is a differential amplifier, which is suitable for the acquisition of the differential signal provided by the sensors. It provides an amplified single-mode output signal with 10 V/V gain. Subsequently, this amplified signal is filtered by the MAX7404 integrated circuit. This is a low-pass filter that is used as antialiasing filter with a cut-off frequency adjustable between 1 Hz and 10 kHz. Depending on the

sampling rate selected by the user (i.e. 100 Hz, 250 Hz, 500 Hz and 1000 Hz), the cut-off frequency is set up with the following values: 40 Hz, 100 Hz, 200 Hz and 400 Hz respectively.

Finally, the amplified and filtered signal is connected to a programmable gain amplifier, the LTB5 chip, in order to provide the system with a 3-bit digital gain control. The LTB5 chip is an inverting amplifier with rail-to rail output. It allows selecting among eight different voltage gains (i.e. 0, 1, 2, 5, 10, 20, 50 and 100). The gain is set up by the CMOS-Level digital gain control inputs (pins 5, 6 and 7). These pins are connected to the Arduino Due digital I/O pins (D05, D06 and D07 respectively) (Figure 2). The capacitor, C4, between the MAX7404 output and the LTB5 input, sets the lower cut-off frequency of the amplifier. The value of 470  $\mu$ F sets the lower cut-off frequency in 0.03 Hz, 0.07 Hz, 0.17 Hz and 0.34 Hz for gains of 1, 2, 5, 10 and higher, respectively.

The assemblies of the signal conditioning circuit for one channel and the complete Geophonino-3D are shown in Figure 3.

The complete system can be powered by the USB port of the laptop used for the system configuration or by an external battery. In Figure 4, we show an example of an independent external power module that could be added to Geophonino-3D. It consists in a PowerBoost shield adapter and a Lithium ion rechargeable battery of 3.7V and 2050 mAh. The inclusion of this module is just optional, as it is not a necessary requirement for the operation of Geophonino-3D.

## 2.2. Software implementation



The microcontroller board has been programmed using the Arduino Programming language, which is a pseudo C++ language based on Wiring, and compiled with the Arduino 1.5.6-r2 version. Meanwhile, the graphical user interface (GUI), configured to provide a user-friendly data acquisition setup, has been developed using Processing 2.1.2 (<http://playground.arduino.cc/Interfacing/Processing>). The source code for Arduino Due board and developed GUI are available online at <https://github.com/JLSolerLlorens>.

The program flowchart of the developed code is shown in Figure 5. Once it is powered-up, the device remains waiting to receive a message from the user interface by the serial port. Therefore, the first step in the GUI is the selection of the serial port and the connection with Arduino. The second step consists in configuring the data acquisition parameters: File name, recording duration, sampling rate, Arduino amplification and LTB5 amplification. Finally, the last step is the data acquisition process. The acquired data are saved in plain text format in a file stored into a SD card. This file can be downloaded to the computer, but when its size is considerably large, as often happens with seismic noise records, it is recommended to extract the SD card and to read it directly in the computer. The file header contains the configuration of the acquisition parameters, all separated by commas. These parameters are the selected gain for the Arduino amplification, the recording duration, the sampling rate and the selected LTB5 amplification. The lines below the header contain four columns. The first one is the recording time in milliseconds, which is obtained from the Arduino internal clock. The following three columns are the amplitude of the recorded signal (vertical, NS and EW components, respectively), in digital counts.

Two FIFO buffers have been configured to store alternately the data during the acquisition. Besides, a timer interruption has been also programmed to activate the

analog to digital conversion at the times given by the sampling rate selected by the user. This ensures that no sample will be lost. Another timer interruption has been used to generate the clock signal that controls the cut-off frequency of the antialiasing filter (the MAX7404 integrated circuit).

### *2.3. Construction costs*

In order to know the approximate cost of the system at the present time, the main electronic components, together with their respective price, are presented in Table 1. Thus, the total cost of these components is around 95€ The price of the resistors, capacitors and hook-up wires is lower than 5 €and is not included in Table 1. Finally, the cost of the external power module (i.e. the Arduino shield adapter and the battery) is around 35 € It has not been included in Table 1 as it is an optional module, which is not necessary for the operation of Geophonino-3D.

## **3. Results and discussion**

### *3.1. Tests on digitizer*

The influence of different instruments in estimating the local site response using H/V technique on microtremor data was investigated in a previous Instrument Workshop: Site Effects Assessment Using Ambient Excitations [20]. Concretely, the chapter 3 of the corresponding Workshop report is dedicated to test the possible influence of the digitizers. Thus, following the guidelines indicated in this report, we have tested the developed acquisition system in the laboratory in order to assess the reliability and accuracy of Geophonino-3D for seismic noise measurements. Particularly, the performed tests have been the following ones: 1) Experimental sensitivity; 2) internal noise stability; and 3) channel consistency.

#### *3.1.1. Experimental sensitivity*

In order to check the sensitivity on the developed system, the biased voltage, i.e. 1.65V, was connected to the three channels synchronously at normal and inverse polarity. The supplied DC voltage was measured for each channel through a multimeter. Meanwhile, the output voltage was recorded during 30 seconds at the sampling frequency of 100Hz. Thus, the sensitivity was computed dividing the measured DC voltage by the average digital counts measured on the recordings. These measurements were taken five times for each polarity, each one after 10 minutes powering the Geophonino-3D. The mean value and the standard deviation obtained for each polarity are shown in Table 2.

The obtained results show that: i) The polarity does not affect the sensitivity; ii) the three channels have very similar sensitivity and; iii) the theoretical voltage per count,  $\mu\text{V}/\text{counts}$ , is a bit lower than the obtained experimental values, with an error smaller than 2% in the sensitivity. In the previous commented Workshop [20], where 12 commercial digitizers were tested, the estimated errors were between 0.03% and 7.71%.

### *3.1.2. Internal noise stability*

The aim of the internal noise stability test is to study the standard deviation of the internal noise. It was measured experimentally by short-circuiting the Geophonino-3D inputs, and acquiring 10-min signals with a sampling frequency of 100Hz (Figure 6). In order to investigate the noise stability of the digitizer, two classes of measurements, defined as "cold start" (Figure 6a) and "warm start" (Figure 6b), were carried out. In the first one, the noise was acquired after 12 hours minimum without powering the Geophonino-3D. In contrast, the second measurement was taken after 1 hour powering the Geophonino-3D.

The cold start noise presents small drift and high amplitude mainly during the first three minutes of record. After these initial minutes, the standard deviation for each channel is less than 3 digital counts regardless of the type of start, which may be considered a low value compared to the signal level recorded for ambient vibrations [21].

The high amplitude observed in the “cold start” during the first three minutes might be due to the instability of the 5V provided by the USB port, since this voltage varies  $\pm 5\%$  with the computer’s load according to Universal Serial Bus specification.

In order to verify this, the same internal noise stability test described above was done using the external power module (see section 2.1). The obtained results are shown in Figure 7. In this case the standard deviation for each channel is less than 1 digital count and no difference is observed between "cold start" and "warm start".

The tests were repeated three times, both with the USB port and with the external power module, obtaining similar results in each case.

From the obtained results, we can conclude that the standard deviation is low enough regardless of the power supply used. Just in case of using the USB port as power supply, we should avoid the first minutes of recording in the “cold start” mode.

The common procedure used to evaluate the noise level is the comparison with the global high (NHNM) and low (NLNM) noise models published by Peterson [22] (e.g. [23]). They correspond to the upper and lower bound envelopes of a cumulative compilation of representative ground acceleration power spectral densities (PSD) determined for noisy and quiet periods at 75 worldwide distributed digital stations. These noise envelopes were approximated by a sequence of straightline fits and presented in units of dB referred to  $1 \text{ (m/s}^2\text{)}^2/\text{Hz}$  [24]. Since the Peterson curves provide

the limits of the ground motion, we need to convert the electronic self-noise to the equivalent ground motion. For that, we consider a virtual connection with a theoretical 1 Hz sensor [25]. Indeed, it acts as a virtual sensor since no sensors are connected. In this way the power spectral density curves show the lowest possible noise level in the whole frequency band of interest that can be resolved at any site [21].

In Figure 8, the PSD corresponding to the "cold start" and "warm start" measurements are shown for each channel together with the NHNM and NLNM noise models of Peterson [22]. In order to provide a more reliable comparison, we have repeated six times the "cold start" and "warm start" tests and we have estimated an average PSD curve for each channel.

We can observe that the noise levels are within the bounds of the noise models in the frequency band of 0.1 to 10 Hz. Thus, ground motion below this theoretical obtained noise level will produce an output signal smaller than the electronic noise. Besides, all three components present similar PSD levels for frequencies above 0.2 – 0.3 Hz.

Below this frequency, small amplitude differences are observed between the three channels. This might be due to the capacitance tolerance of the 470  $\mu$ F capacitor that controls the lower cut-off frequency of the LTB5 amplifier (see Figure 2).

The lower cut-off frequency is 0.34 Hz for a gain of 10, which is the one used in the tests. However, the capacitor has a tolerance of 20%, which can produce small variations in the cut-off frequency and therefore also in the amplitudes of the signals recorded around this frequency.

In any case, these small amplitude differences appear at frequencies much below the natural frequency of the sensor (1 Hz) and below the cut-off frequency of the LTB5 amplifier (0.34 Hz).

### 3.1.3. Channel consistency

The channel consistency test allows verifying the consistency in time and amplitude between channels. To carry out this test, the three channels of Geophonino-3D were connected to a waveform generator, which provides synchronously a 1Hz triangular signal of 0.1V amplitude. In the ideal case, the signals recorded through the three channels should be the same, so no differences should be observed among them. However, in the real situation some differences are detected, which can be related to time shifts (digitization of the channels at significantly different times) and amplitude variations (corresponding to gain differences) [21].

In Figure 9a, the signals recorded by the three channels have been subtracted among them in order to show the amplitude and time differences. We can observe that the amplitude differences are lower than 2%. Their origin might be found in the intrinsic electronic noise and small voltage gain deviations. Synchronization errors (time differences) between channels have not been observed, since as the peaks of the triangular wave always corresponds to the peaks of the difference signals. Finally, the H/V analysis has been also carried out (Figure 9b). If the same waveform is recorded by the three channels, then the H/V ratio will be equal to 1 in the whole frequency range [20], as it is shown in Figure 9b.

## 3.2. Experimental verification

### 3.2.1. Data Acquisition

To test the suitability of the developed low-cost acquisition system for recording seismic noise and applying the H/V method, we have carried out several field campaigns along the province of Alicante (southeast Spain) and the results obtained

using Geophonino-3D have been compared with the ones obtained using a commercial digitizer. Concretely, the sites selected for the field campaigns have been San Isidro ( $0^{\circ}50'16.68''\text{W}$ ,  $38^{\circ}10'24.24''\text{N}$ ), Rojas ( $0^{\circ}43'12.47''\text{W}$ ,  $38^{\circ}5'30.68''\text{N}$ ), Almoradí ( $0^{\circ}47'0.44''\text{W}$ ,  $38^{\circ}6'41.97''\text{N}$ ), Catral ( $0^{\circ}48'2.46''\text{W}$ ,  $38^{\circ}9'30.12''\text{N}$ ), Elche ( $0^{\circ}43'45.42''\text{W}$ ,  $38^{\circ}16'16.20''\text{N}$ ), Guardamar del Segura ( $0^{\circ}40'46.20''\text{W}$ ,  $38^{\circ}5'18.84''\text{N}$ ), Callosa del Segura ( $0^{\circ}50'14.46''\text{W}$ ,  $38^{\circ}8'44.46''\text{N}$ ), and Muchamiel ( $0^{\circ}26'33.60''\text{W}$ ,  $38^{\circ}24'36.84''\text{N}$ ) (Figure 10), which present different soil characteristics. The seismic noise was recorded with two three-component sensors (Mark L-4C-3D), with a natural frequency of 1Hz. Despite the natural frequency of these sensors is 1Hz, they are appropriated to retrieve resonant frequencies up to 0.2 Hz in H/V analysis, as it is shown in the works of Strollo et al. ([26, 27]). As digitizers, we used the developed Geophonino-3D and the commercial 24-bits digitizer, Reftek, both recording simultaneously. The measures were taken in February and March of 2017, during calm weather, in order to avoid possible wind-induced disturbances at low frequencies in the H/V results.

The data acquisition was configured with the following characteristics: the recording time was 30 min and the sampling frequency was 100Hz. For Geophonino-3D, the selected gain was 0dB (1x) for Arduino amplifier and 20dB (10x) for the LTB 5 amplifier. In the case of the Reftek, unity gain was used.

### 3.2.2. Analysis and results

The suitability of noise recordings for retrieving the resonant frequency (H/V analysis) depends on the instrumental noise of the whole sensor-digitizer instrumental chain and especially, on the energy of the recorded noise. In fact, if such energy is very high at the frequencies we are looking at, then it is possible that, even with the

limitations of the corner frequency of the sensors, they are actually able to capture part of this energy and provide good results.

In order to estimate the energy of the recorded noise and test the suitability of the sensor-digitizer instrumental chain, we have compared the PSD of the normalized recordings from the developed Geophonino-3D and the commercial digitizer, Reftek. In Figure 11, we show the computed PSD of the normalized recordings from Geophonino-3D (blue lines) and Reftek (red lines) for all the analyzed time windows. The average PSDs of the normalized recordings are also shown in these plots with a thick blue/red line, respectively. For all the analyzed sites, the average PSDs show a great consistency between the results obtained using the developed Geophonino-3D and the commercial digitizer, Reftek. These curves present different shapes and amplitudes from one site to other due to the different characteristics of the recorded noise and the underneath soil at the selected sites.

After that, the Sesarray software ([www.geopsy.org](http://www.geopsy.org)) has been used for the H/V analysis. The data has been divided in non-overlapping and 5% cosine tapered 50-seconds windows; and the Konno and Ohmachi [28] window with coefficient  $b=40$  has been used for spectra smoothing. Then, combining the amplitude spectra of the horizontal components by a root-mean-square (RMS) average calculation, and dividing it by the amplitude spectra of the vertical component, the H/V ratio has been obtained for all the selected windows. Finally, the mean H/V curve, together with the respective standard deviation, has been obtained by averaging the results from each window.

In Figure 12, the H/V results obtained using Geophonino-3D and the commercial 24-bits digitizer, Reftek, are shown in the right and left columns,



respectively. We can observe that the curves obtained with both instruments are pretty similar, providing practically the same resonant frequencies in both cases.

Only some amplitude differences are observed in the H/V peaks of Catral, Guardamar del Segura and Callosa del Segura. At these sites, the estimated resonant frequency is approximately 0.4, 0.3 and 0.4 Hz, respectively. These frequencies are so close to the lower cut-off frequency established by the 470  $\mu\text{F}$  capacitor and the LTB5 amplifier, that is 0.34 Hz for a gain of 10. Therefore, as it was commented previously in section 3.1.2, the amplitude differences observed between the three channels might be due to the tolerance of the capacitor, which can produce small variations in the cut-off frequency.

In any case, these small amplitude differences between the three channels may affect the amplitude of the H/V peak but not the estimation of the resonant frequency, as it is observed in Figure 12. In this sense, these differences are not important since many authors establish that the amplitude of the H/V peak is not able to give a good estimate of the site amplification factor [29-33].

The lower cut-off frequency could be reduced either by selecting a voltage gain for the LTB5 amplifier lower than 10 (e.g. 0.17 Hz for a gain of 5) or by using a capacitor greater than 470  $\mu\text{F}$ . On the other hand, the small variations in the cut-off frequency might be reduced by selecting a capacitor with smaller tolerance.

As it was commented previously, we have selected sites with different soil characteristics that cover resonant frequencies from 0.3Hz (Guardamar del Segura) to 7.4Hz (Muchamiel). Thus, we have assessed the performance of Geophonino-3D for

frequencies below and above 1Hz, which is the usual frequency range found in microzonation studies.

#### 4. Conclusions

The main objective of this work has been to design and develop a three-component low-cost portable seismic recorder, suitable for passive seismic measurements. Therefore, especial emphasis has been placed on studying the capability of the proposed Arduino based data acquisition system to record seismic noise. In this sense, it has been also crucial the study of the suitability of the recorded seismic signals for the application of the H/V method and the reliable estimation of the resonant frequency that characterizes the subsoil.

In order to assess the performance of Geophonino-3D, three laboratory tests have been carried out to study the experimental sensitivity, the internal noise stability and the channel consistency. All the obtained results are within the range of values provided by commercial equipment. Besides, experimental measurements have been taken at eight sites with different soil characteristics. At each site, simultaneous recordings with Geophonino-3D and a commercial digitizer, Reftek, were performed in order to compare the obtained H/V results. In all the analyzed sites, the curves obtained with both instruments are pretty similar and the estimated resonant frequencies are practically the same. Therefore, the obtained results show the suitability of Geophonino-3D for recording three-component seismic data and the subsequent application of the H/V method.

The developed seismic data recorder has been built based on the Arduino platform, so this is an open source and open hardware system. Besides, it costs a lot less than any available commercial device. Thus, it constitutes an easy to implement and

accessible seismic data recorder for research or teaching purposes. We would like to remark this last statement because it opens new opportunities to small research groups with limited economical resources.

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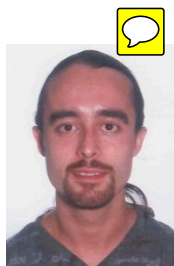
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## Biographies



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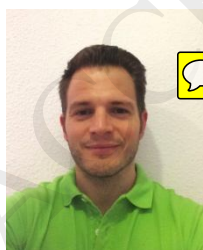
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**Sergio Rosa-Cintas** received his Ph.D. degree in Applied Physics on Sciences of Earth from the University of Alicante (Spain) in 2013. He is currently Professor in the area of Experimental Sciences Teaching at the same university. His main scientific fields are the soil characterization through seismic noise techniques and the research in science teaching. He is also involved in science and popular activities to promote Geology in the background of the province of Alicante (Spain).



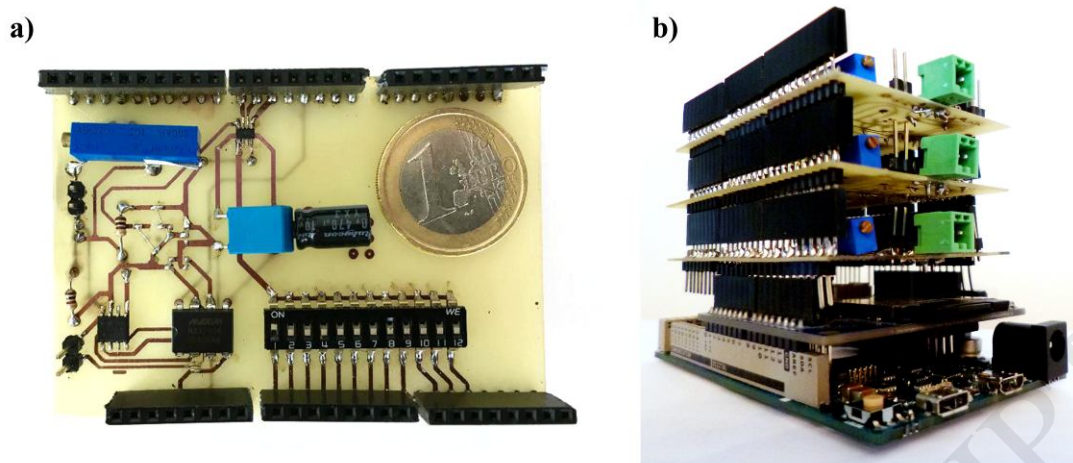
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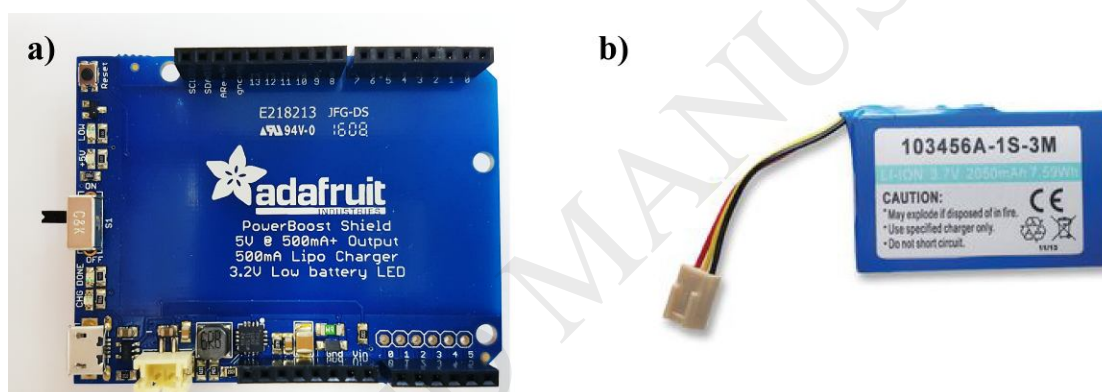
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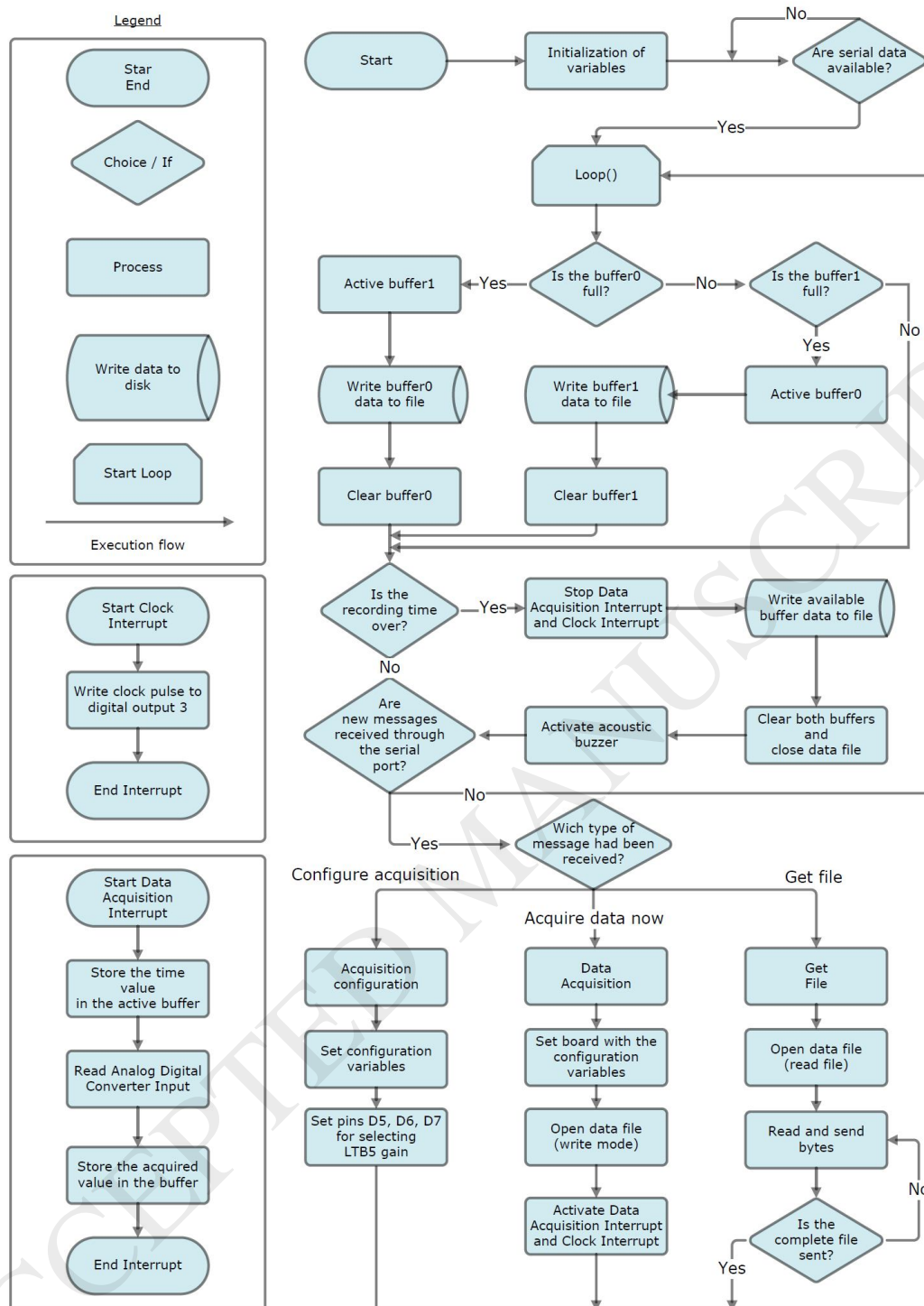




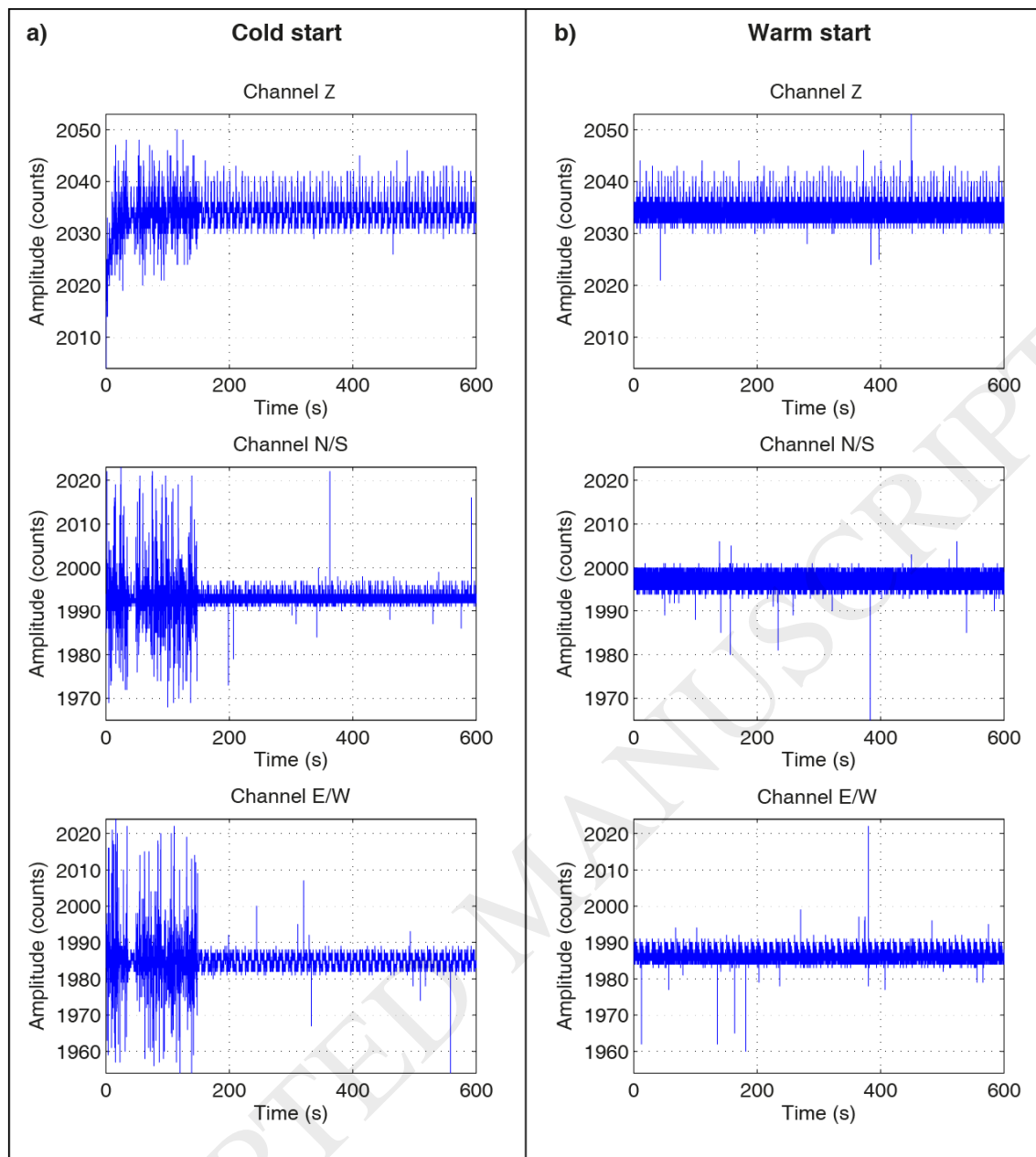
**Figure 3.** Assembled signal conditioning circuit with one-euro coin for scale comparison (a) and Geophonino-3D (b)



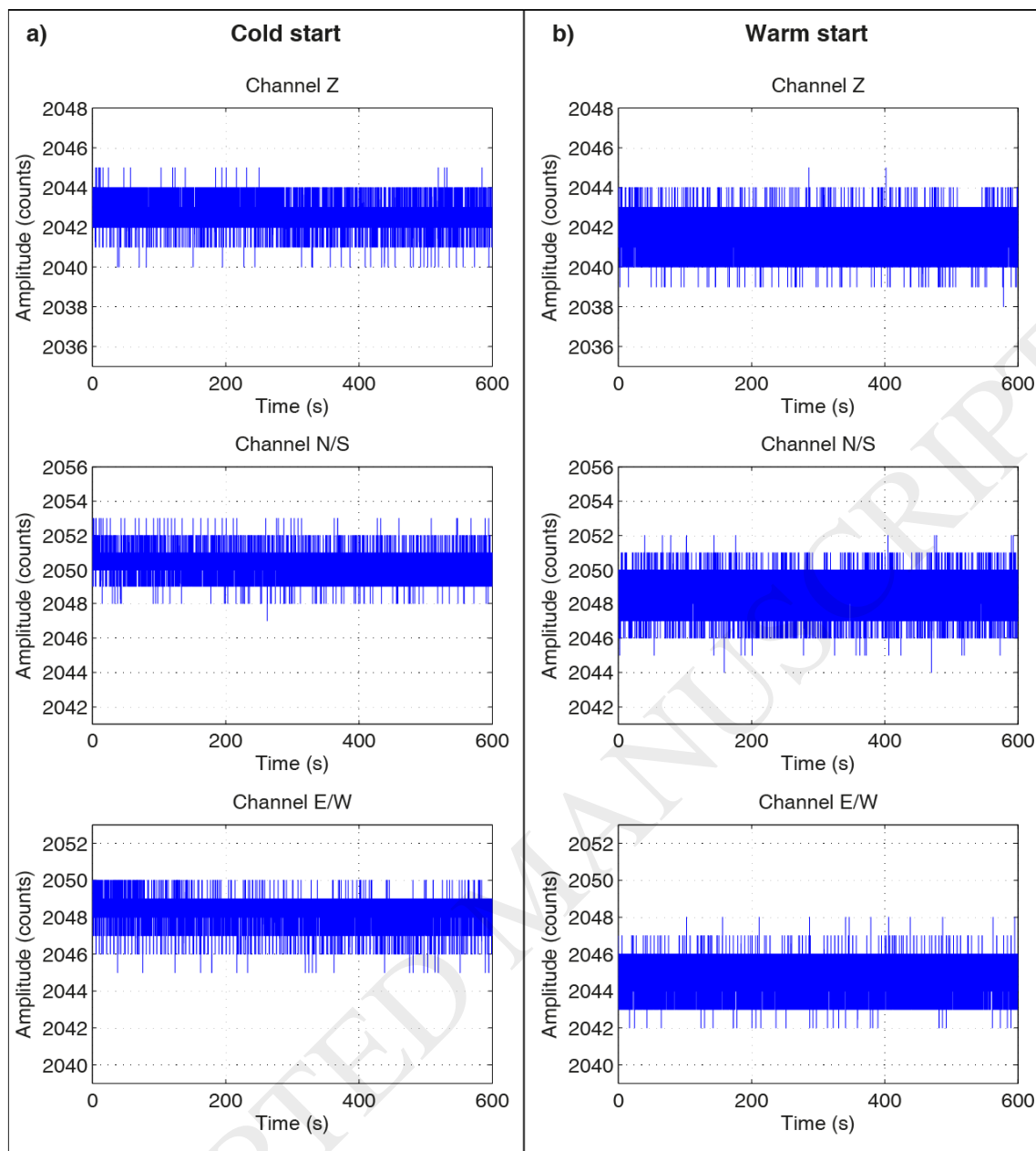
**Figure 4.** PowerBoost shield adapter (a) and Lithium ion rechargeable battery (b)



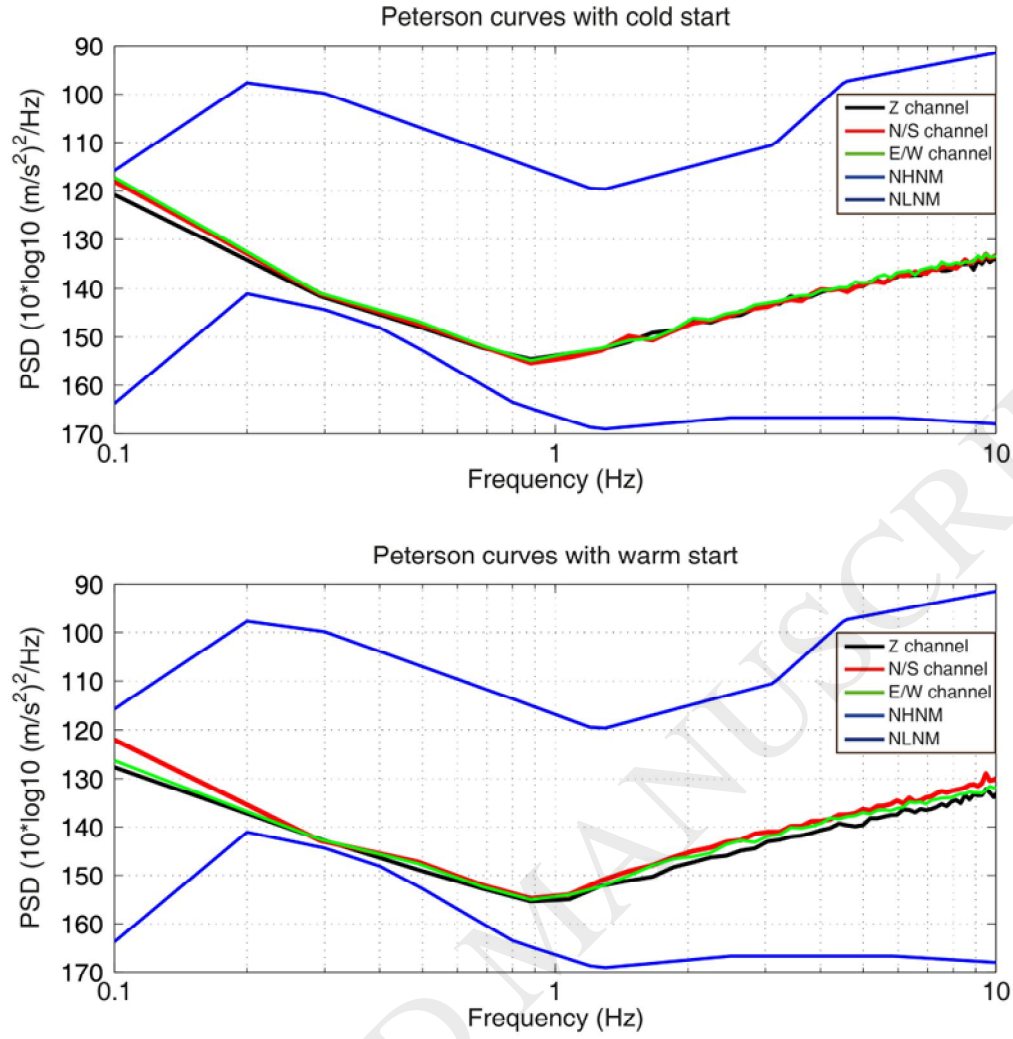
**Figure 5.** Program flowchart of Geophonino-3D.



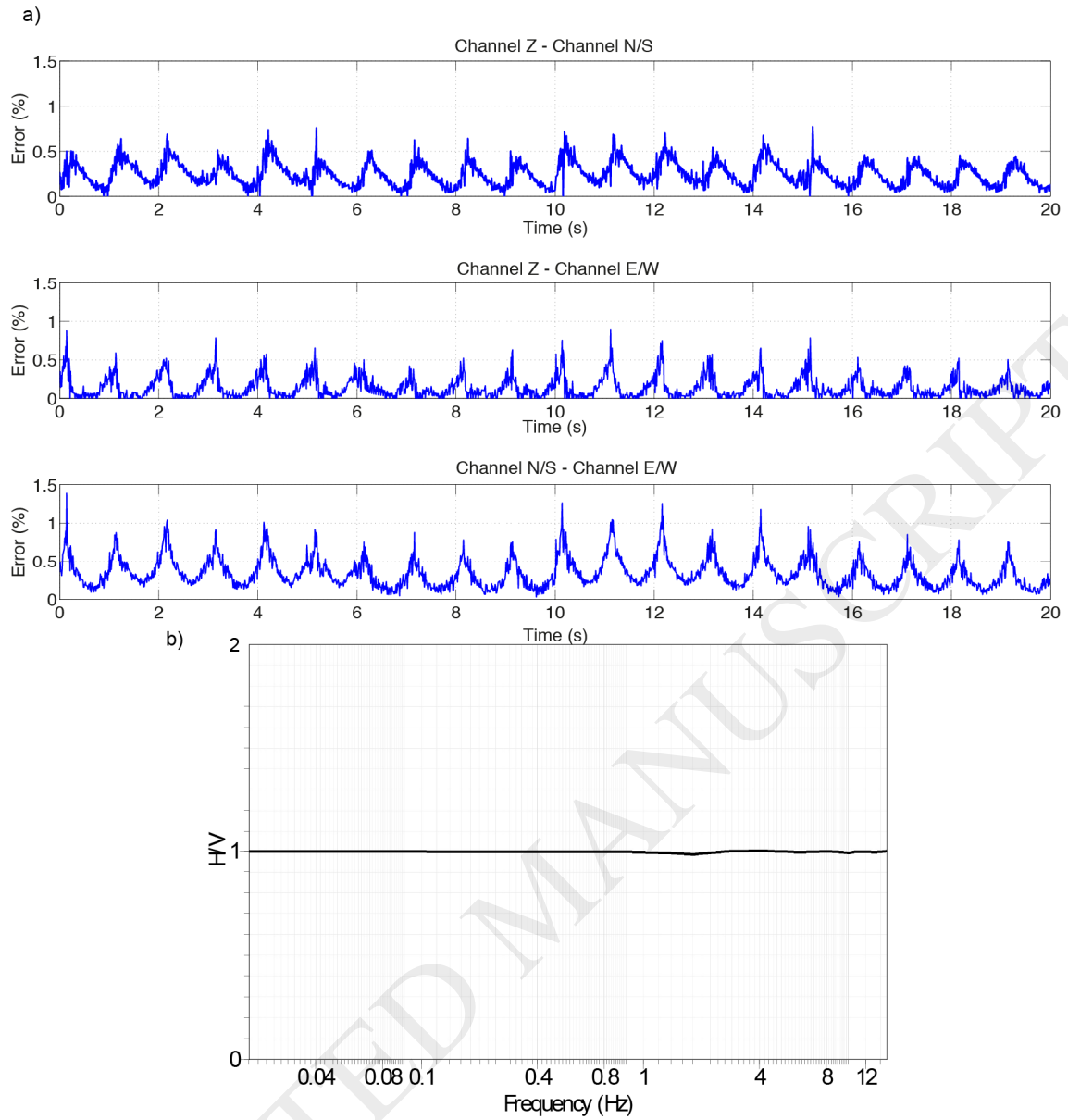
**Figure 6.** Geophonino-3D stability test. Data recorded after cold (a) and warm (b) starts for the three channels using the USB port as power supply.



**Figure 7.** Geophonino-3D stability test. Data recorded after cold (a) and warm (b) starts for the three channels using the external power module.



**Figure 8.** Geophonino-3D internal noise test with a virtual theoretical sensor of 1 Hz [25], in cold (a) and warm (b) start. Blue curves correspond to high-noise (NHNM) and low-noise (NLNM) models from Peterson [22].



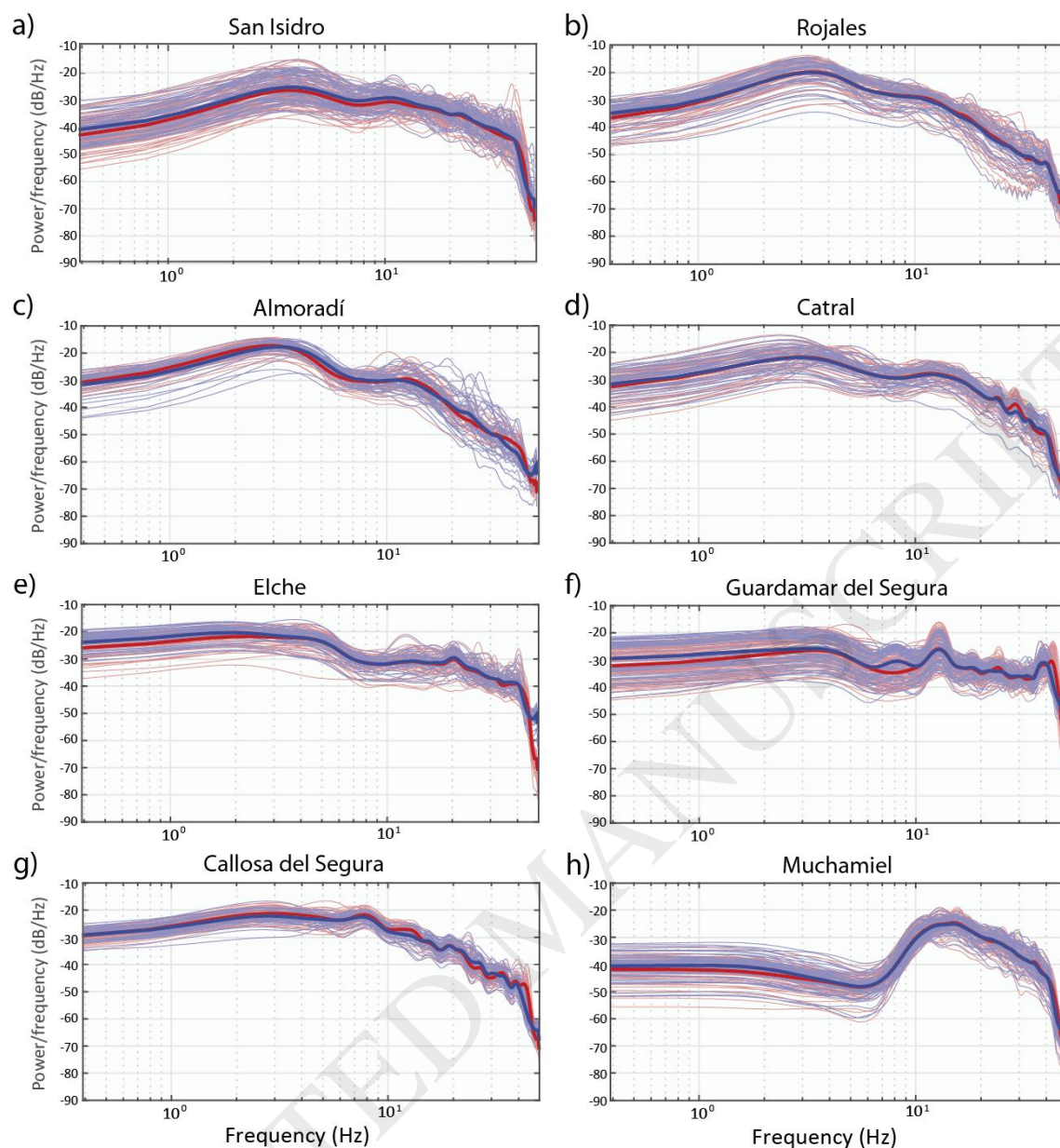
**Figure 9.** Channel consistency test using a 1Hz triangular signal of 1V amplitude applied simultaneously to the three channels. a) Difference signals (expressed in %) for the data recorded by the three channels of Geophonino-3D. b) H/V ratio, with H being the quadratic mean of the two horizontal components.



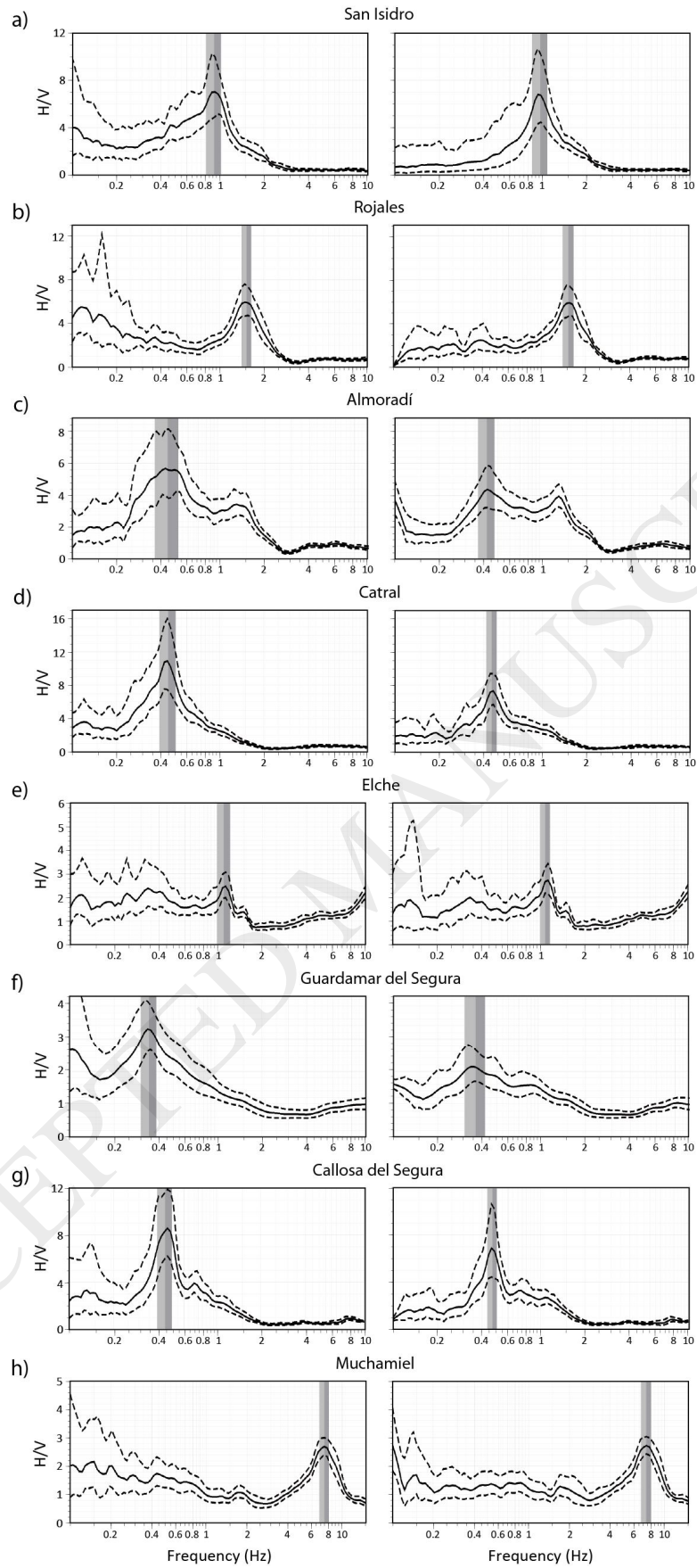


**Figure 10.** Map of the province of Alicante (southeast Spain). The locations of the H/V measurements are shown by red dots.





**Figure 11.** PSD of the recordings from Geophonino-3D (blue lines) and Reftek (red lines) for the analyzed sites. The average PSDs are also shown with a thick blue/red line, respectively



**Figure 12.** H/V curves (mean value and standard deviation) obtained using Geophonino-3D (right column) and Reftek (left column) for all the analyzed sites.

**Table 1.** Main components of Geophonino-3D

| Component                            | Manufacturer      | Cost (€)  |
|--------------------------------------|-------------------|-----------|
| Arduino Due                          | Farnellelement 14 | 1 x 42. 0 |
| SD CardShield V3.0                   | Itead Studio      | 1 x 3. 0  |
| SD Card 8 GB                         | Pc Componentes    | 1 x 8. 0  |
| INA155 amplifier                     | Farnellelement 14 | 3 x 4. 0  |
| MAX7404 filter                       | MouserElectronics | 3 x 6. 0  |
| LTB5 (6910-1) programmable amplifier | Farnellelement 14 | 3 x 3. 0  |
| Speaker - 3" Diameter                | Adafruit          | 1 x 2. 0  |
| TOTAL COST                           |                   | 95. 0     |

**Table 2.** Experimental sensitivity results of Geophonino-3D

|  | Geophonino-3D<br>Normal polarity | Geophonino-3D<br>Inverse polarity |
|--|----------------------------------|-----------------------------------|
| Sampling rate (Hz)   | 100.00                           | 100.00                            |
| Dynamic range (bits)   | 12.00                            | 12.00                             |
| Gain (dB)  | 20.00                            | 20.00                             |
| Theoretical voltage per count ( $\mu\text{V}/\text{count}$ ) | 805.66                           | 805.66                            |
| Z channel  |                                  |                                   |
| Measured voltage per count ( $\mu\text{V}/\text{count}$ )    | 819.62                           | 808.71                            |
| Deviation from theoretical voltage (%)                       | 1.70                             | 0.38                              |
| N/S channel  |                                  |                                   |
| Measured voltage per count ( $\mu\text{V}/\text{count}$ )    | 814.34                           | 818.23                            |
| Deviation from theoretical voltage (%)                       | 1.07                             | 1.53                              |
| E/W channel  |                                  |                                   |
| Measured voltage per count ( $\mu\text{V}/\text{count}$ )    | 812.16                           | 812.38                            |
| Deviation from theoretical voltage (%)                       | 0.80                             | 0.83                              |